THE STRUCTURE OF THE POMERON

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Abstract

Results of experiments probing the structure of the pomeron at hadron colliders and at HERA are reviewed. By renormalizing the pomeron flux factor in diffraction dissociation as dictated by unitarity, a picture emerges from the data in which the pomeron appears to be made of valence quark and gluon color-singlets in a combination suggested by asymptopia.

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1 Introduction

The success of Regge theory in describing the main features of high energy hadronic cross sections with a *universal* pomeron trajectory [1, 2] has generated considerable interest in the nature of the pomeron and its QCD structutre. Since the pomeron has the quantum numbers of the vacuum, it must be represented by a color-singlet $q\bar{q}$ and/or gluon combination of partons. The question whether or not this combination has a unique hadron-like structure can ultimately be answered only by experiment. In this paper we review briefly the results obtained so far by experiments probing the pomeron constituents and draw a coherent conclusion about the partonic structure of the pomeron.

The pomeron structure has been under study in *hard* single diffraction dissociation in hadron colliders and in deep inelastic diffractive scattering at HERA. Events with a rapidity gap between jets observed by CDF and D0 are undoubtedly also related to the pomeron. The phenomenology associated with extracting information on the pomeron structure from these studies relies on Regge theory and factorization. It is therefore useful to review briefly this phenomenology, particularly since unitarity requirements that must be imposed on the theory have a profound effect on the conclusions that can be drawn from the data about the pomeron structure.

The cross section for single diffraction dissociation in Regge theory has the form

$$\frac{d^2\sigma_{sd}^{ij}(s,\xi,t)}{dtd\xi} = \frac{1}{16\pi} \beta_{i\mathcal{P}}^2(t) \, \xi^{1-2\alpha(t)} \left[\beta_{j\mathcal{P}}(0) \, g(t) \left(\frac{s'}{s_0'} \right)^{\alpha(0)-1} \right] \tag{1}$$

where $\mathcal{P}$ stands for pomeron, s' is the s-value in the $\mathcal{P} - j$ reference frame, s_0' is a constant conventionally set to 1 GeV^2, $\xi = s'/s$ is the Feynman-x of the pomeron in hadron-i, and $\alpha(t)$ the pomeron trajectory given by

$$\alpha(t) = \alpha(0) + \alpha't = 1 + \epsilon + \alpha't \tag{2}$$

Fig. 1 shows the Feynman diagrams for the total, elastic, and single diffractive cross sections, including the "triple-pomeron" diagram for single diffraction which is used to derive Eq. (1). The term in the square brackets in (1) may be interpreted as the total cross section of the pomeron with hadron-j,

$$\sigma_t^{\mathcal{P}j}(s',t) = \beta_{j\mathcal{P}}(0) \, g(t) \left(\frac{s'}{s_0'} \right)^{\alpha(0)-1} \tag{3}$$

where $g(t)$ is the pomeron-pomeron coupling, commonly referred to as the *triple-pomeron* coupling constant. Such an interpretation assigns to the pomeron a hadron-like *virtual reality*, which leads naturally to viewing single diffraction as being due to a flux of

pomerons emitted by hadron-i and interacting with hadron-j. The "pomeron flux factor", which in this picture depends on $\beta_{i\mathcal{P}}^2(t)$ and therefore can be obtained from the $i - i$ elastic scattering differential cross section, is identified as

$$f_{\mathcal{P}/i}(\xi, t) = \frac{1}{16\pi} \, \beta_{i\mathcal{P}}^2(t) \, \xi^{1-2\alpha(t)} \tag{4}$$

The assumption of factorization of the flux factor in *hard* processes is coupled to the idea that the pomeron may have a partonic structure similar to that of hadrons. However, even in the absense of such a hadron-like structure, pomeron exchange must involve partons and therefore one should expect to observe hard processes in single diffraction dissociation. Factorization allows such processes to be calculated for any particular experiment from the pomeron flux factor and an assumed partonic structure for the pomeron. The question of the uniqueness of the pomeron structure can then be answered by comparing the results of different experiments with expectations.

A model based on this view was proposed by Ingelman and Schlein (IS) and was used to calculate high-P_T jet production in $p\bar{p}$ single diffraction dissociation [3]. This calculation was followed by the discovery of diffractive dijets by UA8 [4]. The shape of the η-distribution of the jets in the UA8 experiment favors a hard structure function for the pomeron, of the type $F(\beta) = 6\beta(1 - \beta)$, where β is the momentum fraction of a parton inside the pomeron, over a soft structure function of the type $F(\beta) = 6(1 - \beta)^5$. However, the dijet rates calculated for such a structure function using the IS model are substantially higher than the observed ones. The "discrepancy factor" required to multiply the pomeron hard-quark(gluon) structure function to predict the measured dijet rates is $0.46 \pm 0.08 \pm 0.24$ ($0.19 \pm 0.03 \pm 0.10$) [5]. One possible explanation for this result is that the *virtual* pomeron does not obey the momentum sum rule [5, 6]. A more physical explanation, in which the pomeron *obeys* the momentum sum rule, is offered by interpreting the pomeron flux as a probability density for finding a pomeron inside hadron-i and *renormalizing* it so that its integral is not allowed to exceed unity [7]. Using a renormalized pomeron flux lowers the predicted rates, thereby increasing the discepancy factors mentioned above by a factor of ~ 4 and bringing the UA8 results into agreement with the momentum sum rule.

The renormalization of the pomeron flux was proposed in order to unitarize the triple-pomeron amplitude, which gives the single diffractive cross section. Without unitarization, the $p\bar{p}$ SD cross section (Eq. 1) rises much faster than that observed, reaching the total cross section and therefore violating unitarity at the TeV energy scale. This is shown in Fig. 2, taken from [7], which compares data with predicted $p\bar{p}$ SD cross sections obtained with and without a renormalized pomeron flux. The renormalized flux is given by

$$f_N(\xi, t) = f_{\mathcal{P}/i}(\xi, t) d\xi dt \qquad \text{for} \ \ N(\xi_{min}) \leq 1$$

$$f_N(\xi, t) = \frac{f_{\mathcal{P}/i}(\xi, t)d\xi dt}{N(\xi_{min})} \qquad \text{for} \quad N(\xi_{min}) > 1 \tag{5}$$

$$\text{with} \quad N(\xi_{min}) \equiv \int_{\xi_{min}}^{0.1} d\xi \int_{t=0}^{\infty} f_{\mathcal{P}/i}(\xi, t)dt$$

where $\xi_{min}=(1.5 \text{ GeV}^2/s)$ for $p\bar{p}$ soft single diffraction. Below, experimental results on hard diffraction will be compared with predictions obtained both with the standard and a renormalized pomeron flux.

2 Hard diffraction at hadron colliders

Single diffraction dissociation provides the most transparent and accessible window for looking at the structure of the pomeron. Events are tagged as diffractive either by the detection of a high-x_F (anti)proton, which presumably "emitted" a small-ξ pomeron, or by the presense of a rapidity gap at one end of the kinematic region, as shown in Fig. 3. Another process involving the pomeron is hard *double* diffraction dissociation, which is characterized by a rapidity gap in the central region and one or more jets on each side of the gap. Below, we review briefly the hard diffraction collider experiments and discuss the interpretation of their results in terms of a pomeron structure function.

2.1 The UA8 experiment

UA8 pioneered hard diffraction studies by observing high-P_T jet production in the process $p + \bar{p} \to p + Jet_1 + Jet_2 + X$ at the CERN $Sp\bar{p}S$ collider at $\sqrt{s} = 630$ GeV. Events with two jets of $P_T > 8$ GeV were detected in coincidence with a high-x_F proton, whose momentum and angle were measured in a forward "roman pot" spectrometer. The event sample spanned the kinematic range

$$0.9 < x_p < 0.94 \qquad\qquad 0.9 < |t| < 2.3 \text{ GeV}^2$$

Assuming the jets to be due to collisions between the proton and pomeron constituents, and comparing the x_F distribution of the sum of the jet momenta of the events with Monte Carlo distributions generated with a standard proton but different pomeron structure functions, UA8 concluded [4] that the partonic structure of the pomeron is $\sim 57\%$ *hard* $[6\beta(1 - \beta)]$, $\sim 30\%$ *superhard* $[\delta(\beta)]$, and $\sim 13\%$ *soft* $[6(1 - \beta)^5]$. However, the dijet production rate measured by UA8 [5] is smaller by a factor of ~ 2(or 5) than the rate predicted for a pomeron made of hard-quark(or gluon) constituents obeying the momentum sum rule. As discussed in the introduction, this discrepancy between the results obtained by the event shape and event rate analyses was expressed by UA8 in terms of a coefficient by which the full quark or gluon hard structure function has to be

multiplied to yield the measured rates. This coefficient, named "the discrepancy factor", represents the fraction of the pomeron momentum carried by its partons. As already discussed, with the standard flux normalization the UA8 hard pomeron does not obey the momentum sum rule. Using the procedure of pomeron flux renormalization, the discrepancy factors of $0.46 \pm 0.08 \pm 0.24$ $(0.19 \pm 0.03 \pm 0.10)$ measured by UA8 for a hard-quark(gluon) dominated pomeron become $1.79 \pm 0.31 \pm 0.93$ $(0.74 \pm 0.11 \pm 0.39)$ [7]. These values are both consistent with unity, so that the momentum sum rule is restored. Assuming the momentum sum rule to be exact, the rate analysis could in principle be used to measure the ratio of the quark to gluon component of the pomeron. However, the present UA8 results are not accurate enough to address this issue.

2.2 Diffractive W's in CDF

The quark content of the pomeron can be probed directly with diffractive W production, which to leading order occurs through $q\bar{q} \rightarrow W$. A hard gluonic pomeron can also lead to diffractive $W's$ through $gq \rightarrow Wq(\rightarrow W + Jet)$, but the rate for this subprocess is down by a factor of order α_s. The ratio of diffractive to non-diffractive $W^{\pm}(\rightarrow l^{\pm}\nu)$ production has been calculated by Bruni and Ingelman (BI) [8] to be $\sim 17\%$ $(\sim 1)\%$ for a hard-quark(gluon), and $\sim 0.4\%$ for a soft-quark pomeron structure. Thus, diffractive W production is mainly sensitive to the hard-quark component of the pomeron structure function. However, the rates calculated by BI may be too optimistic. Using the renormalized pomeron flux lowers the hard-quark prediction down to 2.8% [7].

A search for diffractive $W's$ is currently being conducted by the CDF collaboration at the Tevatron at $\sqrt{s} =$1800 GeV using the rapidity gap technique to tag diffraction. Preliminary results from a study of a sample of $\sim 3,500$ W events show no signal for diffractive W production at the level of *a few %* [9], which is to be compared with the 17% of the BI and the 2.8% of the renormalized flux predictions. This result, therefore, restricts severely the hard-quark structure function of the pomeron for the BI-type flux, but lacks the sensitivity needed to probe the pomeron structure if the renormalized flux factor is used.

2.3 Diffractive dijets in CDF

The rapidity gap method was also used in CDF to search for diffractive dijet production, which, as in the UA8 experiment, is sensitive to both the quark and the gluon content of the pomeron. Because of the higher energy used at the Tevatron, $\sqrt{s} = 1800$ GeV as compared to 630 GeV at the $Sp\bar{p}S$, dijets in the same diffractive mass-region as UA8, $M_X^2 \sim 150$ GeV^2, are produced with lower pomeron ξ, since $\xi \approx M_X^2/s$. The signature for such events is two high-P_T jets on the same side of the rapidity region and a rapidity

gap on the other side. Since the rapidity gap method integrates over t, and because of the exponential t-behavior of the diffractive cross section, the average t-value of the events in CDF is close to zero, in contrast to UA8 for which $|t| \sim 1.5$ GeV^2. Probing the structure of the pomeron with the same hard process but different pomeron ξ and t can address the question of the uniqueness of the pomeron structure.

From a study of 3415 events with two jets of $P_T > 20$ GeV and $|\eta| > 1.8$, CDF has obtained the preliminary result of $R \leq \approx 1\%$ at 95% CL for the ratio of diffractive to non-diffractive dijets [10], to be compared with the predictions of $\sim 5\%$ and $\sim 0.6\%$ obtained with the standard and renormalized pomeron flux for a hard-gluon pomeron structure. Again, this result restricts the hard partonic component of the pomeron if the standard flux is used to predict rates, but places no restrictions if the renormalized flux is used.

2.4 Hard double diffraction in CDF and D0

In double diffraction dissociation both the proton and the antiproton dissociate by exchanging a pomeron. The process is characterized by two diffractive clusters of particles with a rapidity gap in-between. The gap is due to the *colorless* QCD nature of the pomeron, as a result of which the two diffractive clusters are not color-connected and therefore there is no radiation between them. A *hard* pomeron can also "kick out" jets into each diffractive cluster and lead to dijet events with a rapidity gap between the jets. Such events have been observed by both CDF and D0. The fraction of rapidity gap dijet events (more jets can be present in addition to the *leading* jets) to all dijet events with the same kinematics (same η-region and P_T) was found to be $R_{jets} = (0.85 \pm 0.12^{+0.24}_{-0.12})\%$ and $(1.4 \pm 0.2)\%$ by CDF [11] and D0 [12], respectively. An estimated rate of (1-3)% was predicted by Bjorken [13] on purely QCD grounds. A quantitative connection to double diffraction dissociation was made in [7], where it was pointed out that the measured rate for R_{jets} is the same within error as the rate of $R_{soft} = 1.2\%$ expected for *soft* double diffraction dissociation in which no jets are present. The fact that $R_{jets} = R_{soft}$ suggests that *the same hard pomeron* participates both in soft and in hard diffractive processes.

3 Deep inelastic diffraction at HERA

At HERA, the quark content of the pomeron is being probed directly with virtual high-Q^2 photons in $e^- p$ deep inelastic scattering at $\sqrt{s} \sim 300$ GeV (28 GeV electrons on 820 GeV protons). Both the Zeus and the H1 Collaborations find that in $\sim (5-10)\%$ of the events there is a large rapidity gap between the proton and the other particles, indicating that the virtual photon interacted with a colorless object "emitted" by the

proton, presumably a pomeron. The general conclusion arrived at from the study of these events is that the pomeron structure is mostly hard, but a substantial soft component is also present.

Recently, the H1 Collaboration reported a comprehensive measurement [14] of the diffractive structure function $F_2^D(Q^2, \xi, \beta)$ (integrated over t, which is not measured), where β is the fraction of the pomeron momentum carried by the quark being probed. The measurement was performed in the traditional way used to measure the structure function of the proton, but it was done on events with a rapidity gap. H1 finds that the ξ-dependence factorizes out and that it can be fit for all Q^2 and β bins with the form $1/\xi^{1+2\epsilon}$, which is the same as the expression in the pomeron flux factor, Eq. 4. Moreover, the fit yields $\epsilon \approx 0.1$, which is in agreement with the value measured in *soft* collisions. It therefore appears that *the same pomeron* is involved in hard as in soft collisions, a conclusion that we also reached above in comparing the results of hard double diffraction dissociation with soft double diffraction.

In order to obtain a "picture" of the β-structure of the pomeron and its possible Q^2-dependence, H1 integrates the diffractive form factor $F_2^D(Q^2, \xi, \beta)$ over ξ and provides values for the expression

$$\tilde{F}_2^D(Q^2, \beta) = \int_{0.0003}^{0.05} F_2^D(Q^2, \xi, \beta) d\xi \tag{6}$$

The limits of integration cover the entire range of the experimental measurements, and the integration was carried out even in the cases where the lower limit was kinematically inaccessible. The results for $\tilde{F}_2^D(Q^2, \beta)$ are plotted in Fig. 4a as a function of β for four Q^2-bins: $Q^2 =$8.5, 12, 25 and 50 GeV. Assuming complete factorization of the flux factor, this figure represents the pomeron structure function apart from a normalization factor. The structure appears to be flat in β and has a small but significant Q^2 dependence. However, these conclusions are altered if one uses the renormalized flux of [7]. As discussed in the introduction, the procedure for flux renormalization consists in evaluating the integral of the flux factor over the region $\xi_{min} < \xi < 0.1$ and setting it equal to unity if it is found to be ≥ 1. Now, for fixed Q^2 and β, $\xi_{min} = (Q^2/\beta s)$. Therefore, the flux integral, which to a good approximation varies as $\xi_{min}^{-2\epsilon}$, is given by

$$N(s, Q^2, \beta) \approx \left(\frac{\beta s}{Q^2} \xi_0\right)^{2\epsilon} = 3.8 \left(\frac{\beta}{Q^2}\right)^{0.23} \tag{7}$$

where ξ_0 is the value of ξ_{min} for which the flux integral is unity. For our numerical evaluations we use $\sqrt{s}$=300 GeV and a flux factor with $\epsilon = 0.115$ as in [7]. The value of ξ_0 turns out to be $\xi_0 = 0.004$. Since ξ_0 is larger than ξ_{min} for all points in Fig. 4a, the flux must be renormalized for all the points.

The pomeron structure function is obtained from $\tilde{F}_2^D(Q^2,\beta)$ using factorization:

$$\tilde{F}_2^D(Q^2,\beta) = \left[\frac{\int_{0.0003}^{0.05} d\xi \int_0^\infty dt \, f_{\mathcal{P}/p}(\xi,t)}{N(s,Q^2,\beta)} \right] F_2^{\mathcal{P}}(Q^2,\beta) \tag{8}$$

The expression in the brackets is the normalized flux factor. The integral in the numerator has the value 2.0 when the flux factor of [7] is used. Eq. (8) shows explicitly how factorization breaks down due to flux renormalization. The break-down of factorization is a direct consequence of unitarization. Assuming now that the pomeron structure function receives contributions from the four lightest quarks, whose average charge squared is 5/18, the quark content of the pomeron is given by

$$f_q^{\mathcal{P}}(Q^2,\beta) = \frac{18}{5} F_2^{\mathcal{P}}(Q^2,\beta) \tag{9}$$

The values of $f_q^{\mathcal{P}}(Q^2,\beta)$ obtained in this manner are shown in Fig. 4b. As seen, the renormalized points show no Q^2 dependence. We take this fact as an indication that the pomeron *reigns in the kingdom of asymptopia* and compare the data points with the asymptotic momentum fractions expected for any quark-gluon construct by leading-order perturbative QCD, which for n_f quark flavors are

$$f_q = \frac{3n_f}{16+3n_f} \qquad f_g = \frac{16}{16+3n_f} \tag{10}$$

The quark and gluon components of the pomeron structure are taken to be $f_{q,g}^{\mathcal{P}}(\beta) = f_{q,g}\,[6\beta(1-\beta)]$. For $n_f = 4$, $f_q = 3/7$ and $f_g = 4/7$. The pomeron in this picture is a combination of valence quark and gluon color-singlets and its complete structure function, which obeys the momentum sum rule, is given by

$$f^{\mathcal{P}}(\beta) = \frac{3}{7}[6\beta(1-\beta)]_q + \frac{4}{7}[6\beta(1-\beta)]_g \tag{11}$$

The data in Fig. 4b are in reasonably good agreement with the quark-fraction of the structure function given by $f_q^{\mathcal{P}}(\beta) = (3/7)[6\beta(1-\beta)]$, except for a small excess at the low-β region. An excess at low-β is expected in this picture to arise from interactions of the photon with the gluonic part of the pomeron through gluon splitting into $q\bar{q}$ pairs. Such interactions, which are expected to be down by an order of α_s, result in an *effective* quark β-distribution of the form $3(1-\beta)^2$. We therefore compare in Fig. 4b the data with the distribution

$$f_{q,eff}^{\mathcal{P}}(\beta) = (3/7)[6\beta(1-\beta)] + \alpha_s(4/7)[3(1-\beta)^2] \tag{12}$$

using $\alpha_s = 0.1$. Considering that this distribution involves *no free parameters*, the agreement with the data is remarkable!

4 Summary and conclusion

We have reviewed the experimental measurements on hard diffraction at hadron colliders and on deep inelastic scattering with large rapidity gaps at HERA, and have derived from the data a structure function for the pomeron. Using the Ingelman-Schlein model, in which a flux of pomerons "emitted" by the nucleon interacts with the other nucleon at hadron colliders or with a virtual high-Q^2 photon at HERA, the picture of the pomeron structure that emerges depends on the normalization of the pomeron flux. Two expression for the flux were used: the standard flux used in the literature, and the *renormalized* flux of [7]. Renormalizing the pomeron flux was proposed as a means of unitarizing the triple-pomeron amplitude. Our conclusions do not depend crucially on the particular parametrization of the standard flux, but the process of renormalization alters the picture drastically.

With the standard flux, the quark component of the pomeron at HERA is given by $1.8\, \tilde{F}_2^D(Q^2, \beta)$ (right-hand axis in Fig. 4a), where the factor of 1.8 is 18/5 divided by the integral of the standard flux factor, which is 2.0 in our parametrization. The β-dependence in Fig. 4a is rather flat, and $f_q^{\mathcal{P}}(Q^2, \beta)$ integrates out to an average value of $\bar{f}_q \sim 1/3$. In contrast, UA8 finds a hard structure with very little room for a soft component. Also, a 1/3 hard-quark component would almost saturate the UA8 rate, leaving little room for gluons in the pomeron. Coming now to the CDF results, with such a structure one would predict a diffractive to non-diffractive W fraction of $\sim 6-8\%$, depending on the flux parametrization, which is to be compared with the preliminary result of less than *a few %*. Thus, the standard flux presents a picture of a mostly quark-made pomeron, which does not satisfy the momentum sum rule and is struggling to satisfy the experimenters of HERA, UA8 and CDF.

Flux renormalization restores order by presenting us with a pomeron that obeys the momentum sum rule and satisfies all present experimental constraints. This pomeron consists of a combination of valence quark and gluon color-singlets in a ratio suggested by asymptopia for four quark flavors. In detail, the results obtained with this model are:

- No free parameters are needed to fit the HERA data.

- HERA and UA8 both find a predominantly hard structure with a small soft component, which can be accounted for by gluon-splitting into $q\bar{q}$ pairs or gluon radiation by the quarks of the pomeron.

- For a pomeron consisting of 3/7 quark and 4/7 gluon hard components, the discrepancy factor for UA8 becomes $1.19 \pm 0.18 \pm 0.61$, which is consistent with unity and therefore in agreement with the momentum sum rule.

- The diffractive W production fraction at the Tevatron is predicted to be 1.2%. This value is not in conflict with the CDF null result of *a few %* accuracy.

- The diffractive dijet fraction at the Tevatron for jet $P_T > 20$ GeV and $|\eta| > 1.8$ is predicted to be 0.5%, which is also not in conflict with the CDF measurement.

In conclusion, a pomeron structure function as given by Eq. (11) accounts for all present experimental results when used in conjunction with the renormalized flux of [7].

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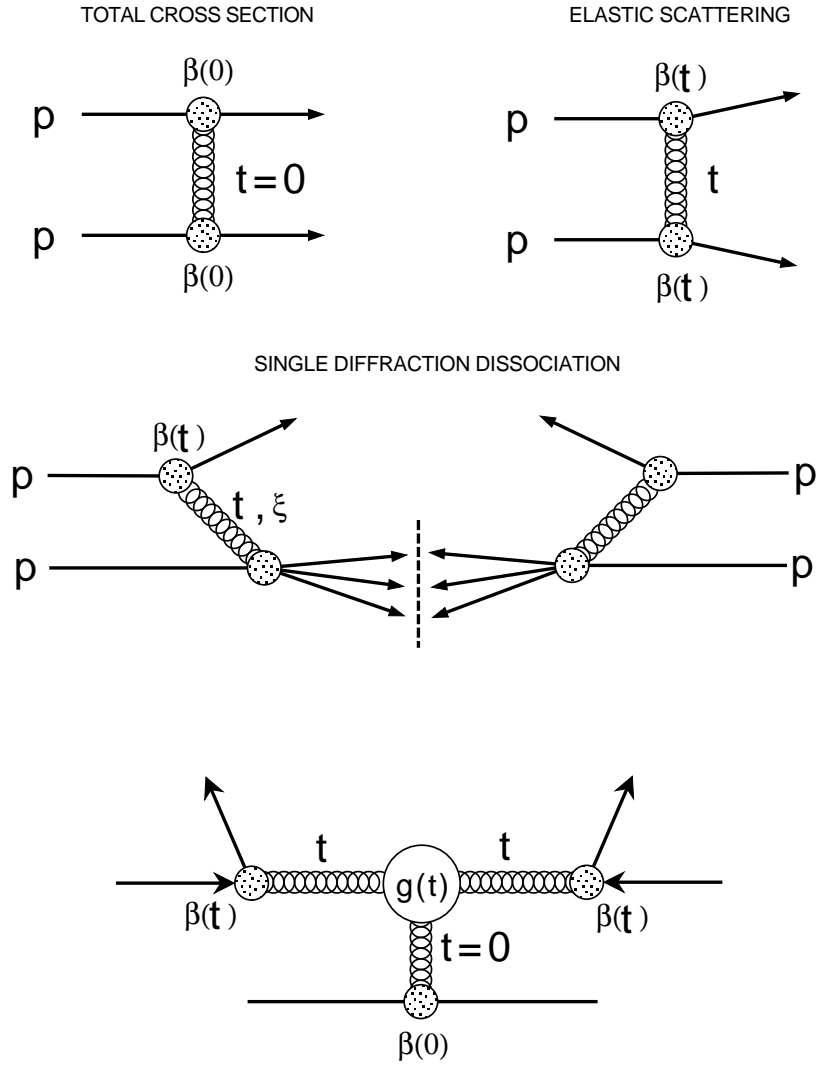
Figure 1: Feynman diagrams for the total, elastic, and single diffraction dissociation cross sections, including the "triple-pomeron" diagram for single diffraction.
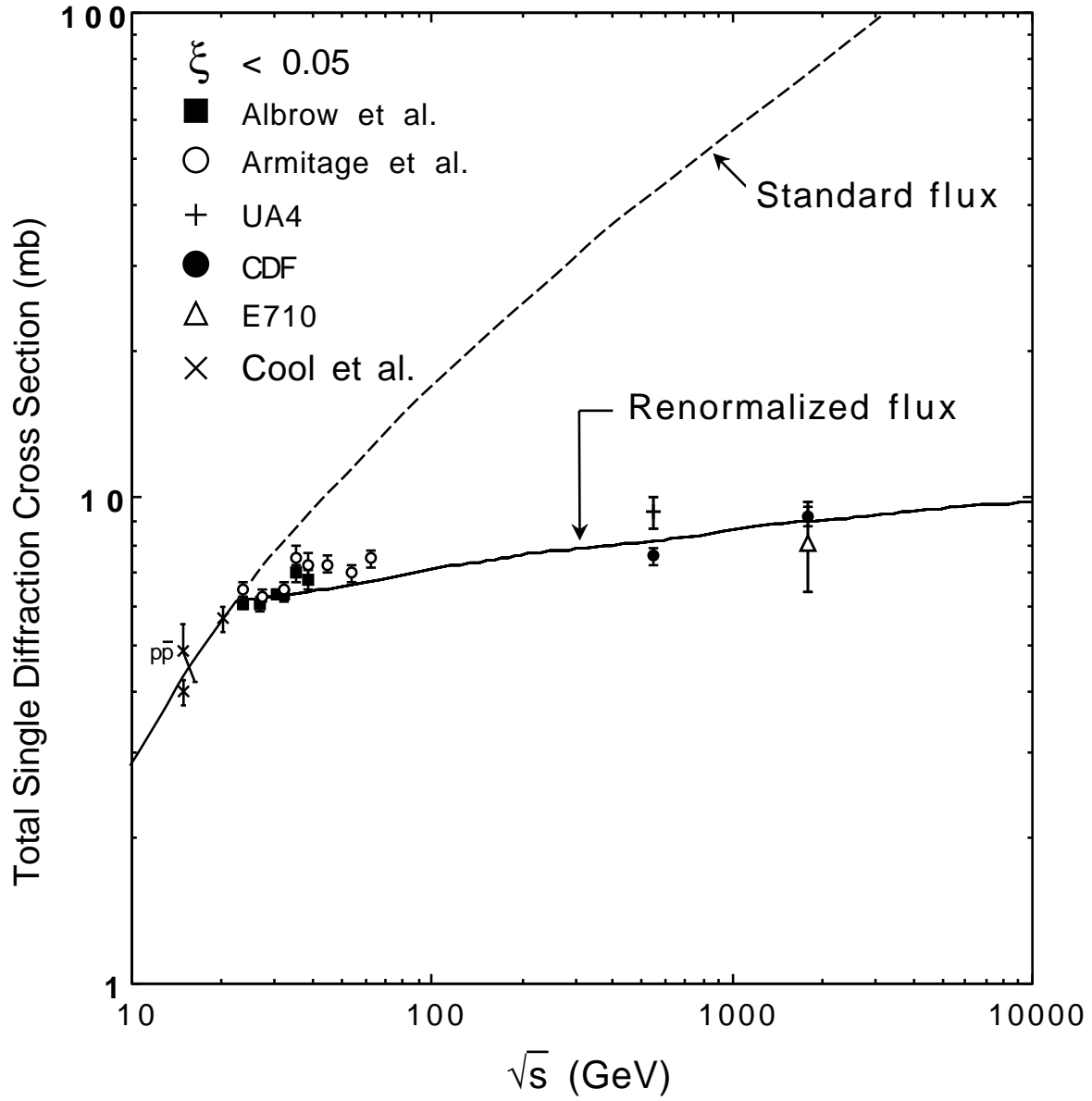
Figure 2: Total $p(\bar{p}) - p$ single diffraction cross section data for $\xi < 0.05$ compared with the predictions of Regge theory with a standard and a renormalized pomeron flux.
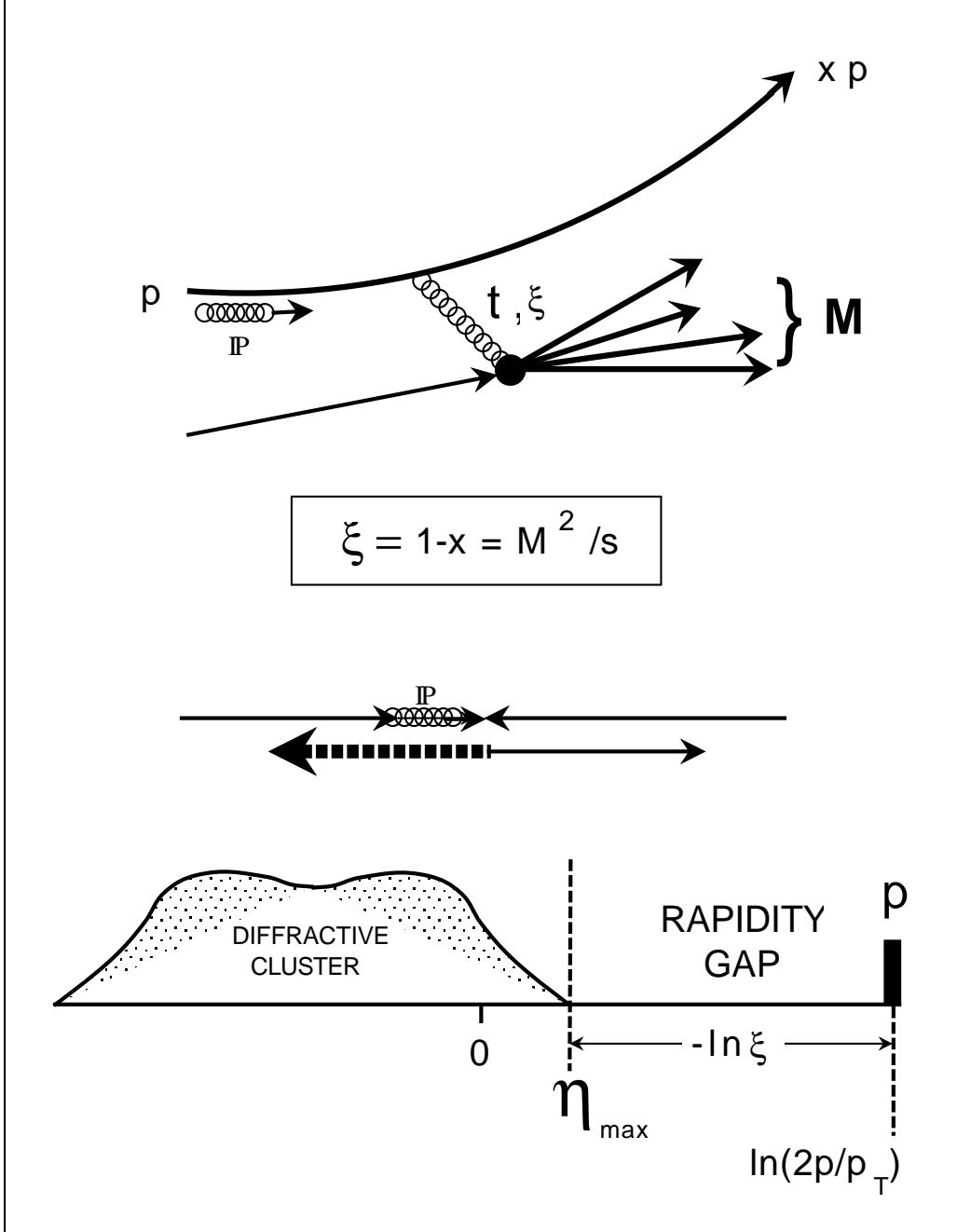
Figure 3: Kinematics for *pp* single diffraction dissociation illustrating the leading particle and rapidity gap techniques for tagging diffractive events.
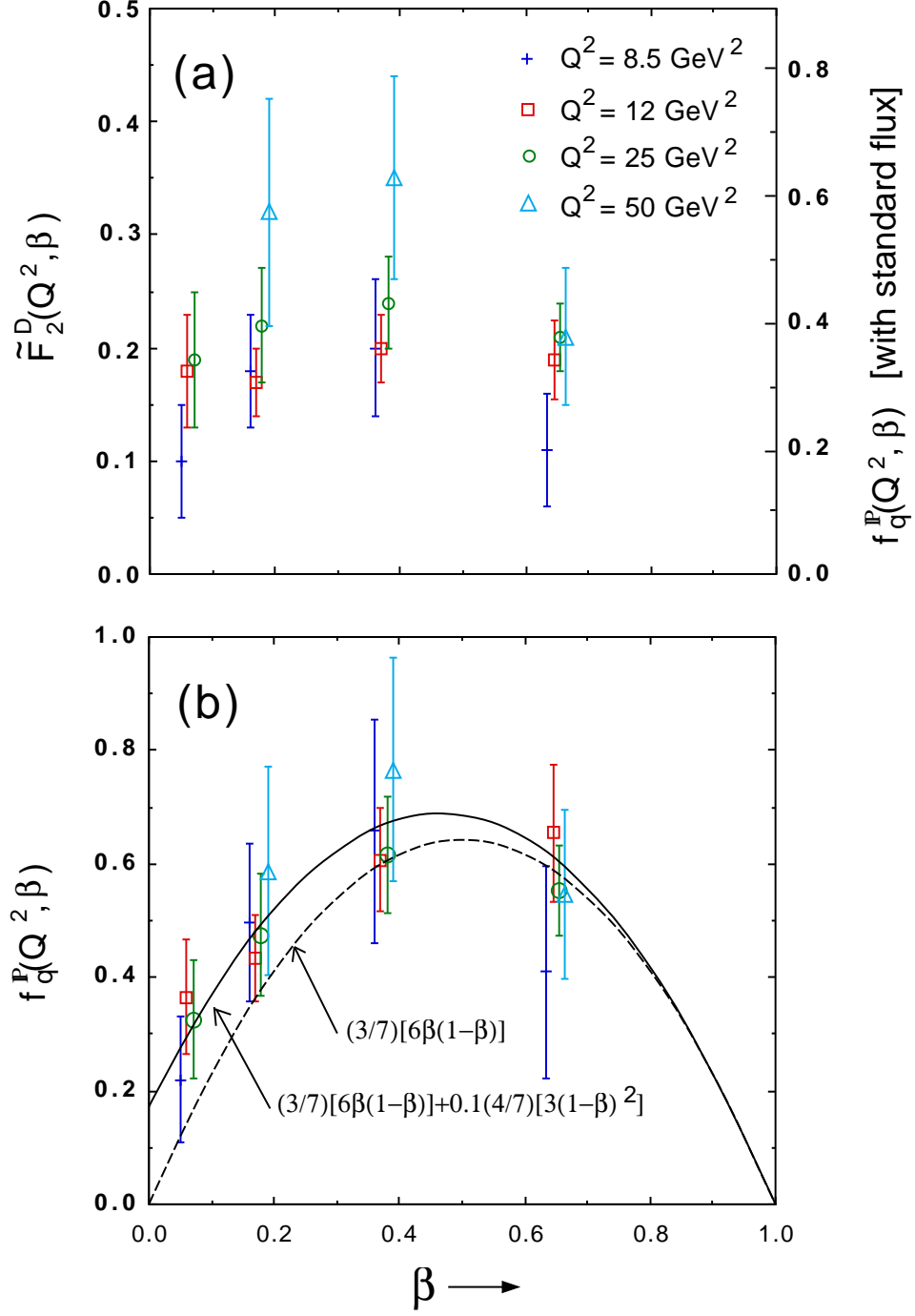
Figure 4: (a) The diffractive structure function measured by H1 at HERA (see Eq. 6); the right-hand y-axis gives the pomeron quark content obtained with the standard flux assuming 4 quark flavors. (b) The pomeron quark structure function obtained using the renormalized pomeron flux.

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